
#3.2 Model Laju Muatan

Elektronika Organik

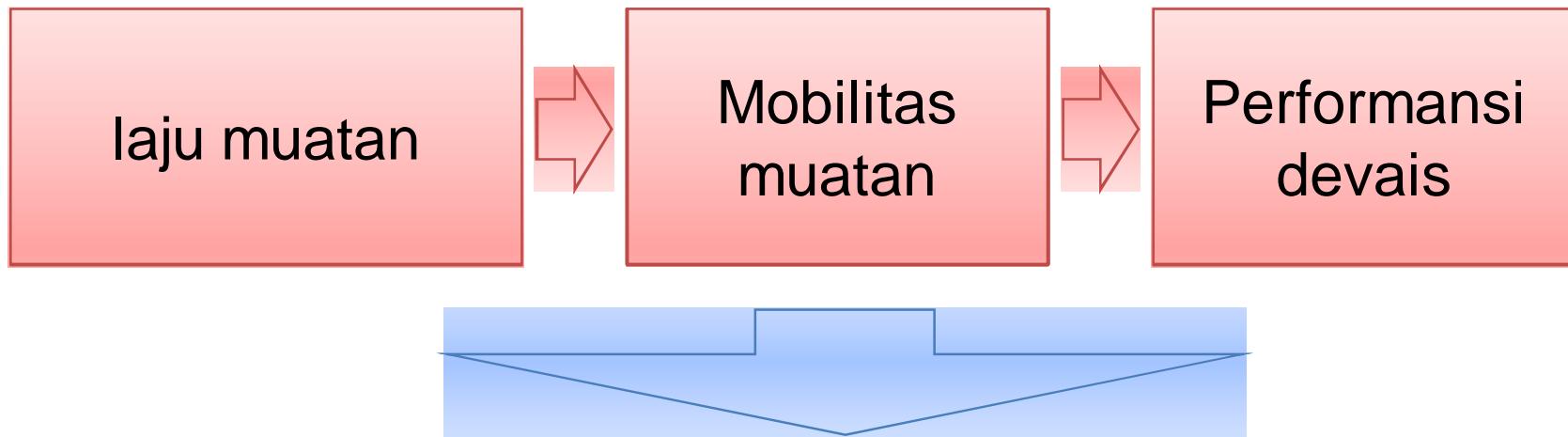
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Universitas Brawijaya

Laju Muatan

- **Tujuan:**

Memberikan pemahaman tentang model laju muatan.

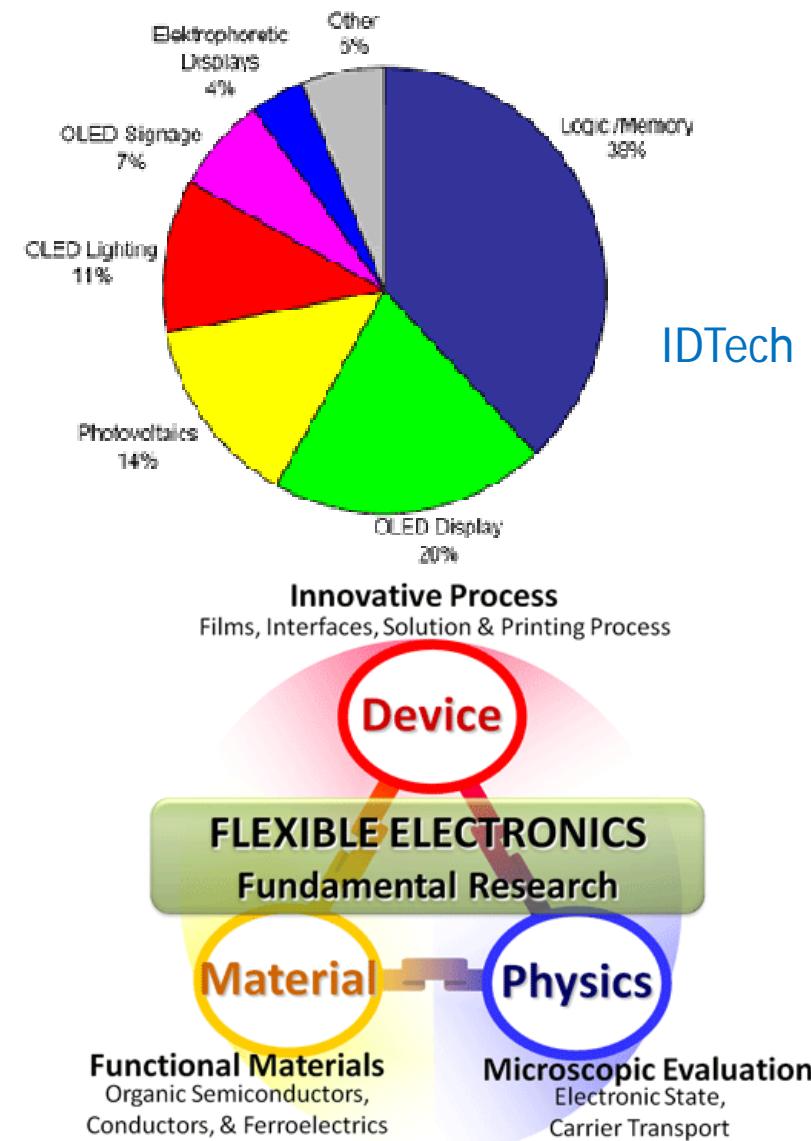


Model hubungan antara pengangkut muatan, fenomena pergerakan muatan,dan mobilitasnya dalam material organik

Prospek dan Peluang Elektronika Organik

- ❑ Organic electronics will be a **\$30 billion business in 2015** mainly due to logic, displays and lighting.
- ❑ It will be a **\$250 billion business in 2025**, with major sales from logic/memory, OLED displays for electronic products, OLED billboard, signage, non-emissive organic displays, OLED lighting, batteries and photo-voltaics
- ❑ Organic lighting will severely dent sales of both incandescent and fluorescent lighting in the second decade from now.
- ❑ Organic electronics in the form of electronic billboards, posters, signage and electronic books will revolutionize the conventional printing and publishing industry.
- ❑ The future organic market will be newly created without replacing much from the inorganic semiconductors in existing electronics products.

SILVACO



Perkembangan

PMOS Project

On Physical Modelling of Organic Semiconductors

Project partners

- Cambridge Display Technology (CDT)
 - Expert in polymer light emitting diode (PLED) technologies
 - Leader in development of solution processable (printable) organic semiconductors for display fabrication
 - Expertise in development of PLED materials and deposition processes
- Silvaco
 - Leading provider of TCAD and EDA software for IC design
 - Provides established products for TCAD process and device simulation, spice parameter extraction, circuit simulation, custom IC design and verification

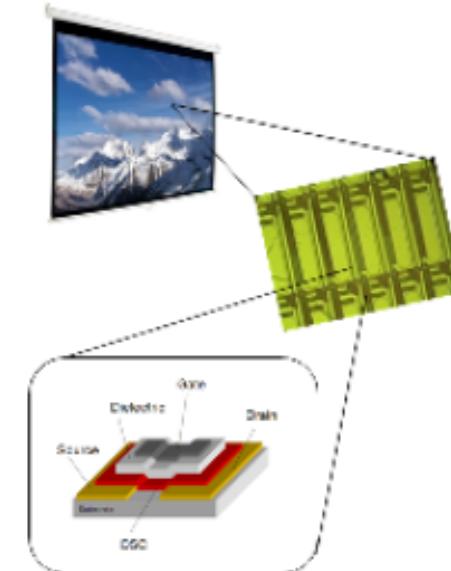
Project activities

- Device fabrication/measurements/testing
- TCAD model development
- Spice model development
- Measurements and modelling of device reliability and aging effects
- The focus is on display device (oled) drivers as these will be the first large scale organic semiconductor products.

OTFT Requirements for OLED Backplanes

OTFTs offer the potential to reduce cost and increase functionality of OLED backplanes.

- Device performance requirements:
 - Mobility ($>0.5\text{cm}^2/\text{Vs}$ with $10\mu\text{m}$ channel)
 - Contact resistance ($<5\text{k}\Omega\text{cm}$)
 - On/Off ratio ($>10^5$)
 - Swing (<1 preferred)
 - Threshold voltage (<0)
 - Current and bias stress stability (mobility and V_{th})
- Process requirements:
 - Low cost: Development of novel solution processing and self-aligned processes
 - Thermal stability in combination with low-T processes (planarisation, OLED fabrication, etc...)
 - Air stability preferred for ease of fabrication (But: OLEDs require encapsulation)



Karakteristik Mobilitas Muatan

Perpindahan rata-rata kuadrat suatu Muatan

$$\langle x^2 \rangle = nDt$$

D: Koefisien Difusi

n: 2,4,6 untuk 1D, 2D, dan 3D

t: waktu

Mobilitas Muatan (Persamaan *Einstein-Smoluchowski*)

$$\mu = \frac{eD}{k_B T}$$

e: muatan elektron

k_B : konstanta Boltzman

t: waktu

v: kecepatan muatan

F: Amplitudo medan Listrik yg diberikan

$$\mu = v/F$$

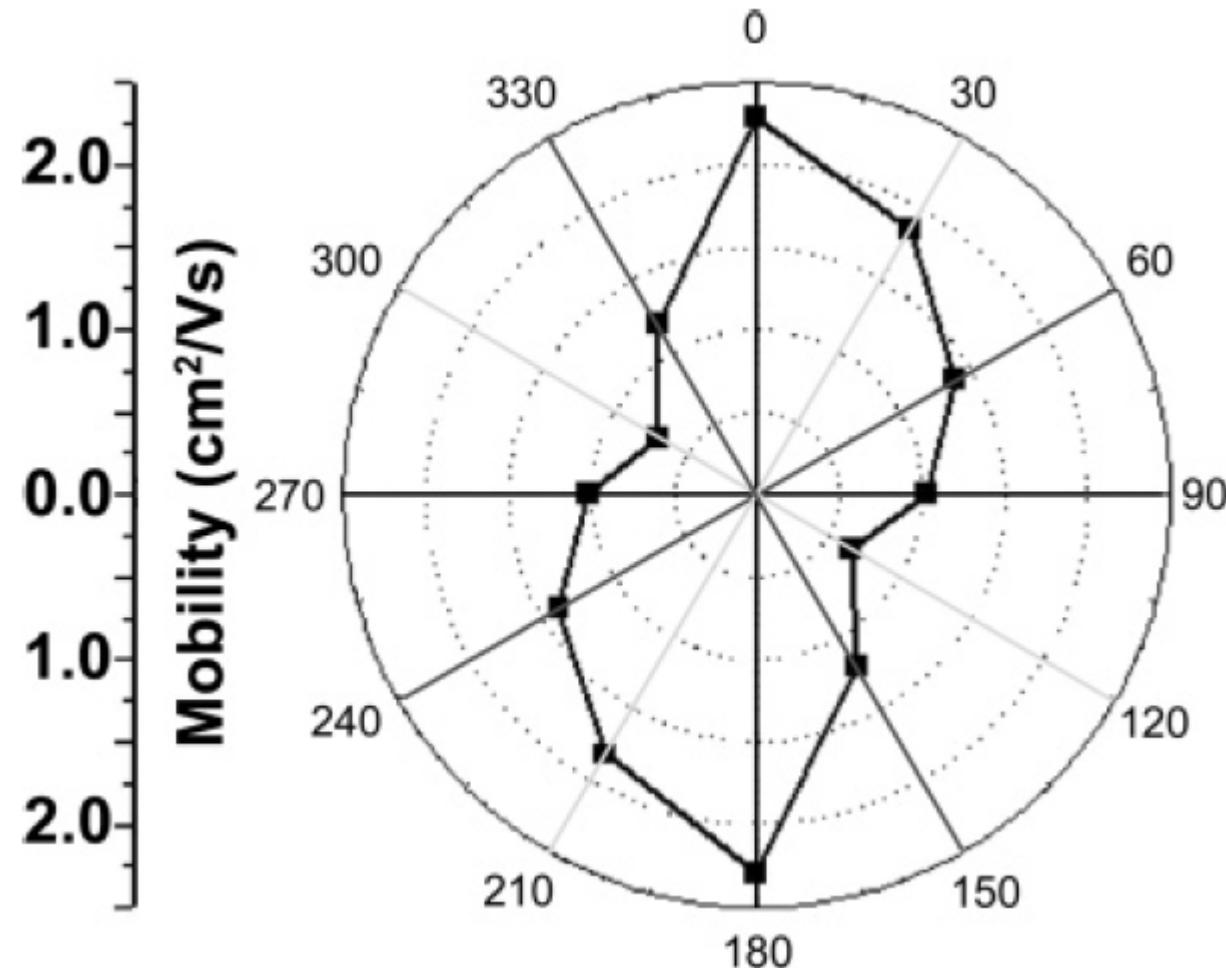
$$\mu = \frac{v}{F} = \frac{d}{Ft} = \frac{d^2}{Vt}$$

d: jarak antar elektroda

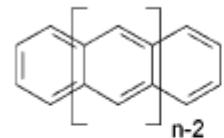
t: rata** waktu transien

V: tegangan antar elektroda

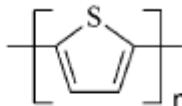
Mobilitas anisotropi pada layer herringbone dalam FET single-crystal pentacene



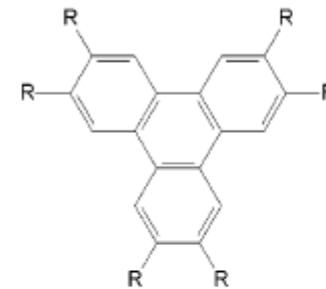
Molekul Semikonduktor Organik



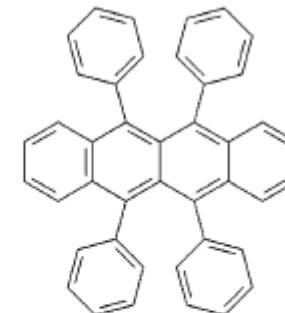
Oligoacenes



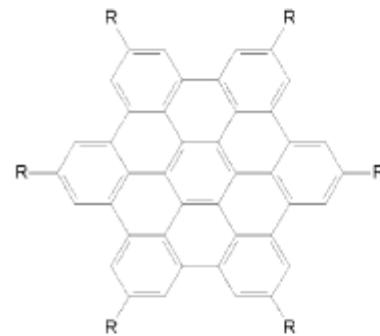
Oligothiophenes



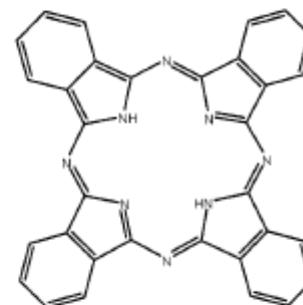
Triphenylene



Rubrene



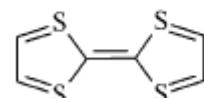
Hexabenzocoronene



Phthalocyanine



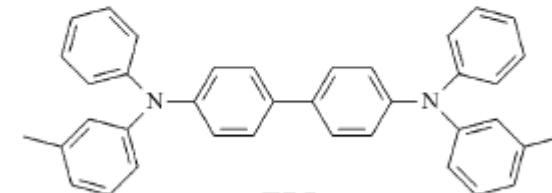
PTCDA ($X=O$)
PTCDI ($X=NH$)



TTF

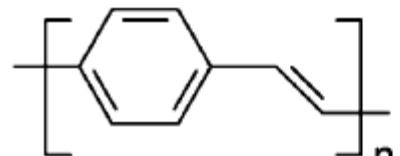


C₆₀

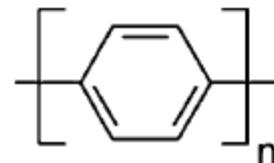


TPD

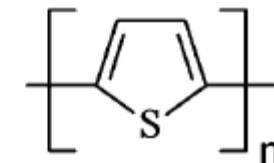
Struktur Kimia Semikonduktor Organik



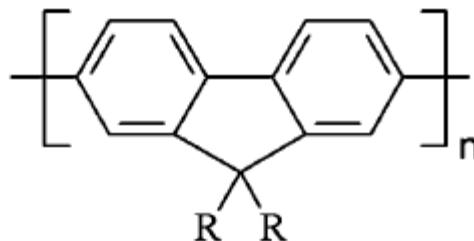
PPV



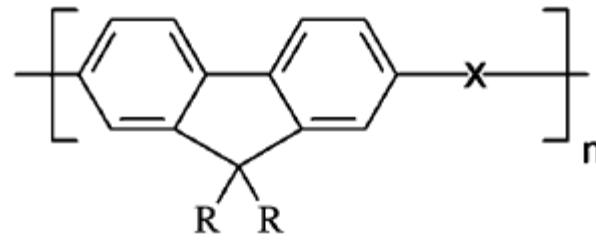
PPP



PT



PF



PF copolymer

Polyparaphenylenevinylene (PPV)

polyparaphenylenes (PPP)

polythiophene (PT)

polyfluorene (PF)

polyfluorene copolymers

(where X stands for various (hetero)cycles)

Mobilitas Muatan

- Typical models
 - Carrier Statistics
 - Fermi-Dirac/Boltzmann
 - Band gap narrowing
 - Recombination
 - SRH/Consrh
 - Auger
 - Optical
 - Impact Ionization
 - Selberherr/Grants/Crowell-Sze
 - Local/Non-local
- Differential field dependent mobility

- Mobility

- Low Field Mobility:

$$\mu_n(T) = \mu_{no} \left(\frac{T}{300} \right)^{\alpha_n}$$

- Field Dependent Mobility:

$$\mu_n(E) = \mu_{no} \left[\frac{1}{1 + \left(\frac{\mu_{no} E}{\nu_{satn}} \right)^{\beta_n}} \right]^{\frac{1}{\beta_n}}$$

$$\mu_n(E) = \frac{\mu_{no} + \frac{\nu_{satn}}{E} \left(\frac{E}{E_0} \right)^\gamma}{1 + \left(\frac{E}{E_0} \right)^\gamma}$$

Persamaan Difusi

- Energy Balance/Simplified Hydrodynamic
 - Higher order approximation than Boltzmann Transport
 - Two extra equations representing electron and hole “temperatures”
 - Key parameter - Energy relaxation time
 - Adds two coupled equations to the drift diffusion equation set:

$$\nabla \vec{S}_n = -\vec{J}_n \nabla \psi - W_n - \frac{3k}{2} \frac{\partial(\lambda_n^* n T_n^*)}{\partial t}$$

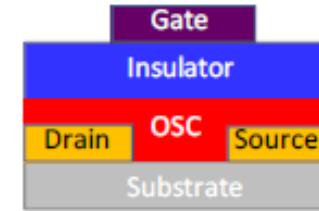
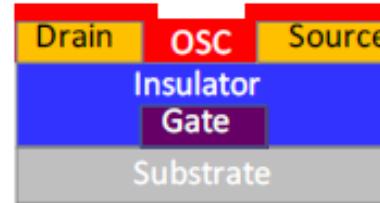
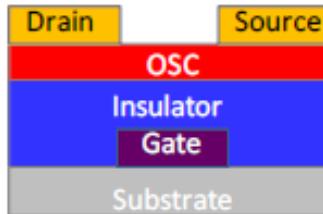
$$\nabla \vec{S}_p = -\vec{J}_p \nabla \psi - W_p - \frac{3k}{2} \frac{\partial(\lambda_p^* p T_p^*)}{\partial t}$$

Persamaan Pasangan Difusi

- Lattice Heating
 - No longer assume lattice temperature is constant
 - Establish thermal boundary conditions
 - H includes generation/recombination, Thomson and Peltier
 - Adds an extra coupled equation to the drift diffusion equation set:

$$C \frac{\partial T_L}{\partial t} = \nabla(\kappa \nabla T_L) + H$$

OTFT Architectures and Peculiar Features



- OTFTs can be fabricated in different device architectures
- OTFTs are commonly realized using an **OSC** layer without a deliberate doping.
- Carriers that contribute to the charge distribution and transport in OTFTs must be injected from the metallic contacts.
- Without particular semiconductor type of the OSC layer, **OTFT** can operate in the electron or hole carrier accumulation mode depending on polarity of the gate voltage and capabilities of the contacts to inject particular carrier type.
- The source and drain have no junction isolation. A drain/source leakage current is limited by intrinsic OSC conductivity and contact resistance rather than reverse junction current.
- Contact resistances often dominate the **OTFT** performance and represent a bottleneck to achieve full potential of the intrinsic transistor effect.
- OTFTs are typically characterized with much lower intrinsic carrier mobility than their inorganic counterparts.

CDT OTFTs:

Architectures/main fabrication steps

CDT explored two device architectures

Bottom gate (BG) bottom contact OTFT

- Gate created by photolithographic patterning of ITO coated glass substrate
- Spin coating of dielectric
- Thermal evaporation of gold contacts through shadow mask
- Before spin coating OSC, self-assembled monolayer treatment is performed (SAM) to ensure matching of energy levels between gold and OSC
- Device encapsulation

Top gate (TG) bottom contact OTFT

- Evaporation of gold (Au) source-drain contacts onto the glass substrate
- Spin coating of organic semiconductor (OSC) onto the surface
- Before spin coating OSC, self-assembled monolayer treatment is performed (SAM) to ensure matching of energy levels between gold and OSC
- Spin coating of dielectric
- Gate (Au or Al) evaporation
- Device encapsulation

CDT OTFTs

Device architecture: pros and cons

Bottom gate bottom contact OTFT

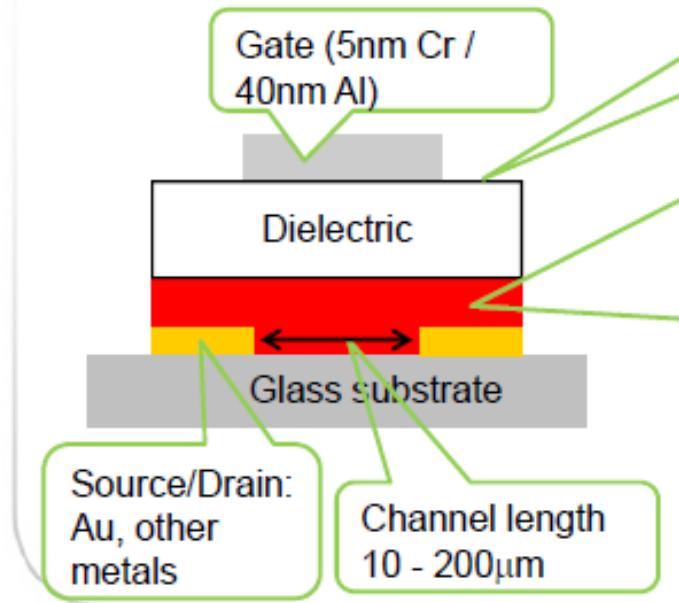
- (+) Wider range of solution processable dielectrics is available
- (+) Smooth dielectric/OSC interface
- (-) Low area for charge injection/extraction in bottom contact - high contact resistance
- (-) Less manufacturable – due to S/D patterning on top of dielectric or OSC

Top gate bottom contact OTFT

- (+) Larger injection area - smaller contact resistance
- (+) More manufacturable
- (+) Dielectric layer provides some level of encapsulation for the OSC
- (-) Dielectric/OSC interface may be more rough
- (-) Limited number of solution processable dielectrics available

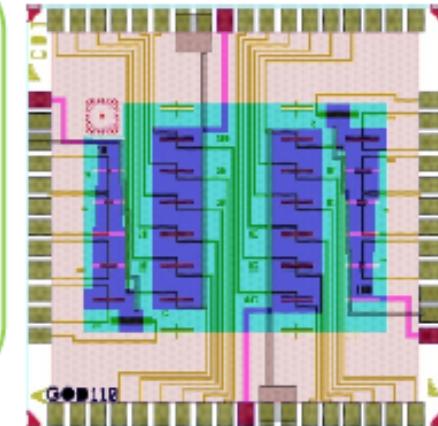
CDT OTFTs: Top Gate Architecture and Materials

- Focus on top gate OTFT architecture
- Avoid damage to critical OSC / dielectric interface
- Lower R_C (greater injection area)
- Novel process development to simplify top gate processing



Fluoropolymer Gate Dielectric (< 250nm)

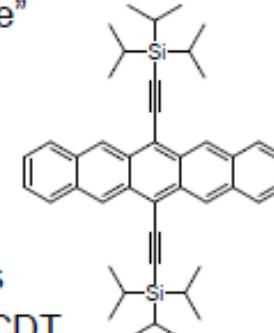
- Fluorosolvent: "orthogonal" to OSC
- Good interface with OSC
- Low-k
- "Encapsulates OSC"



CDT is developing its own proprietary OSC materials

TIPS Pentacene

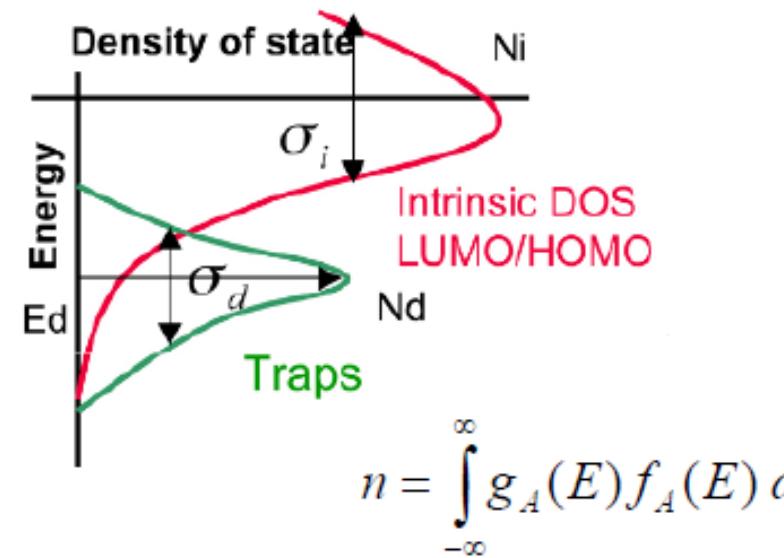
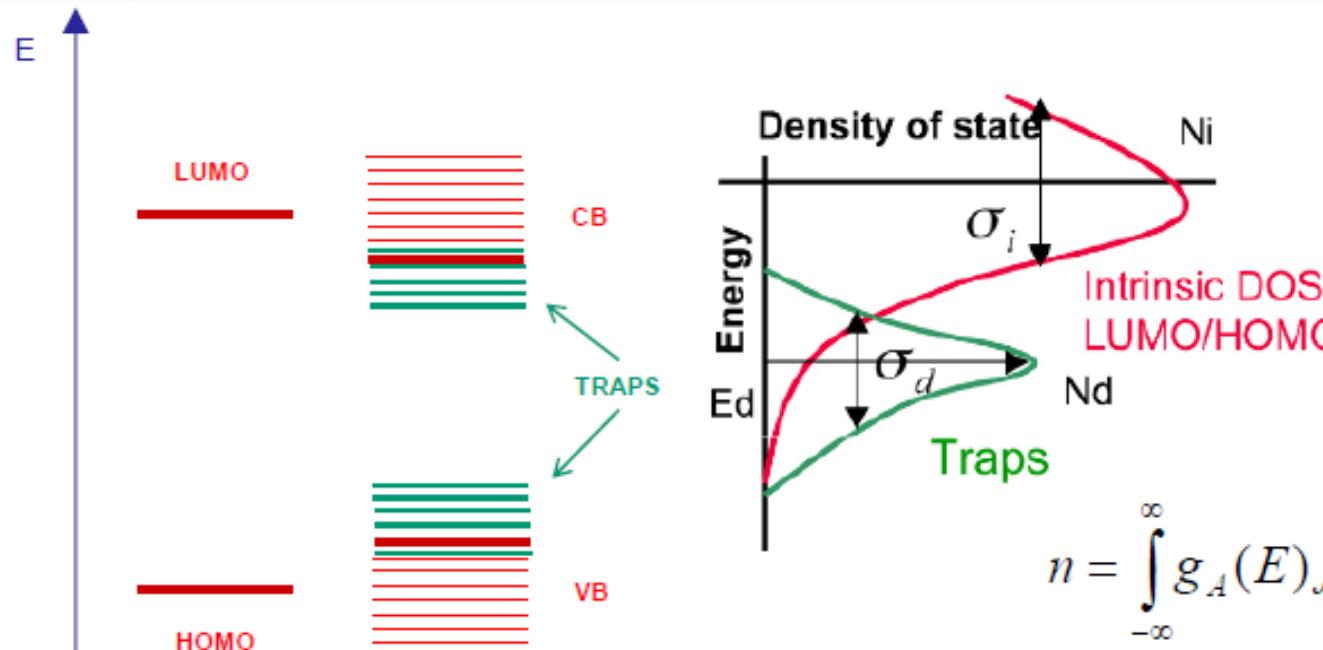
- "Open source" structure
- Well studied in literature
- Mobility of > 1.8 cm²/Vs obtained at CDT



Flexink FS001

- Proprietary material
- Formulation containing a small-molecule oligoacene
- Mobility > 2 cm²/Vs obtained at CDT

Density of States and Carrier Concentration

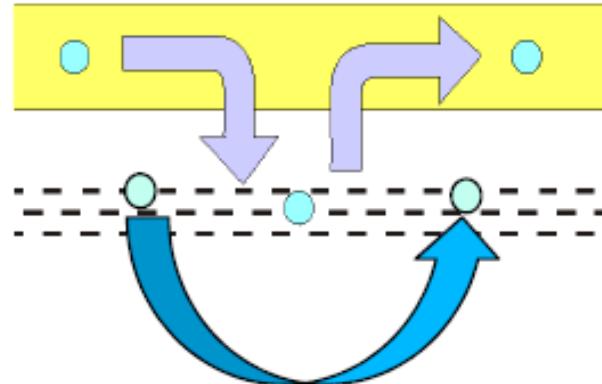


$$n = \int_{-\infty}^{\infty} g_A(E) f_A(E) dE$$

1. Intrinsic DOS from molecular LUMO (HOMO) energy levels ranging from **delocalized conduction and valence bands** in molecular crystals to localized trap-like energy distributions in amorphous OSCs
2. DOS from localized in-gap trap energy levels.

Trap Limited Transport in Organic TFTs

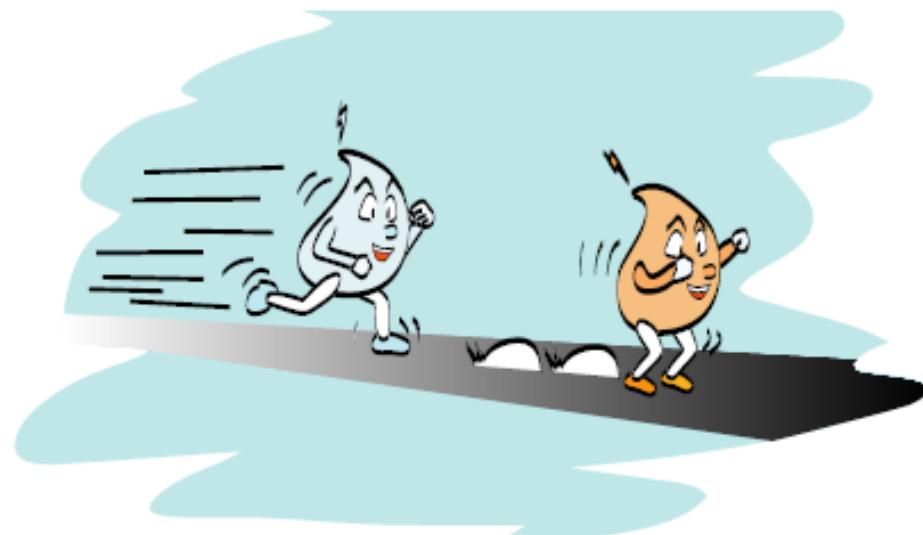
band



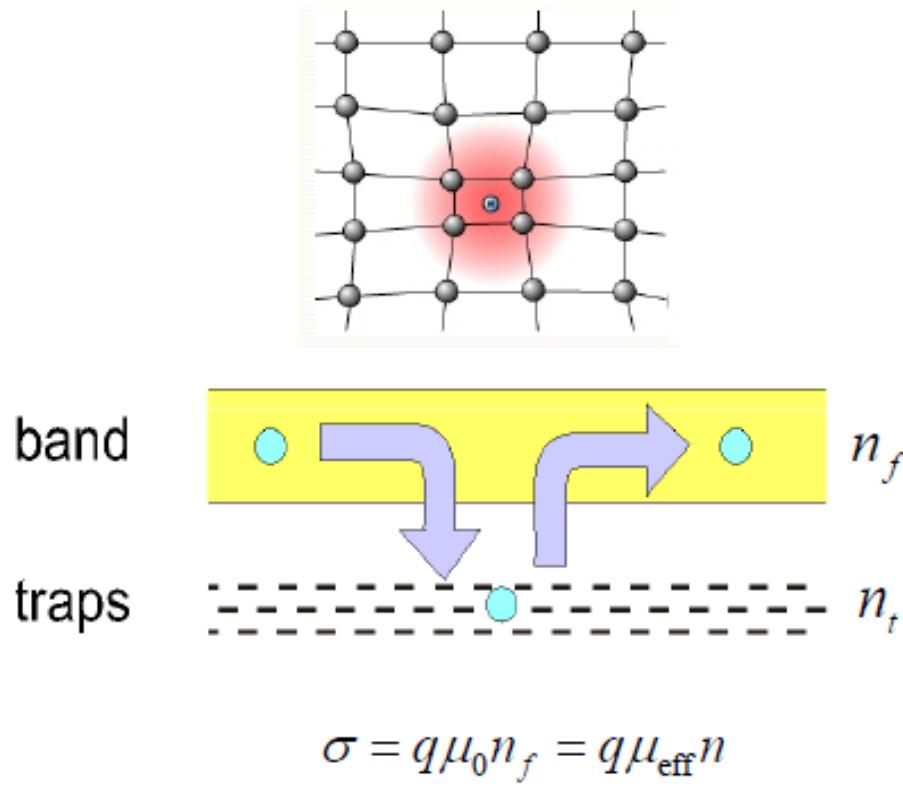
Multiple Trapping and
Thermal Release (MTR)

traps

Variable Range Hopping (VRH)



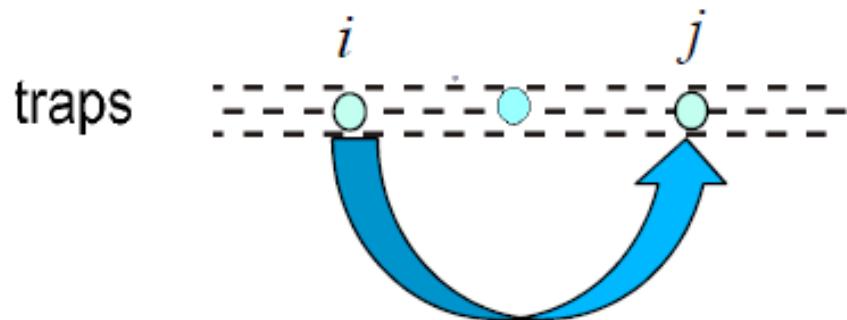
Multiple Trapping and Thermal Release



- Dominant in well-ordered OSCs (molecular crystals)
- Thermally activated mobility
- During the transit in the delocalized band, the charge carriers interact with the shallow localized levels through trapping and thermal release
- The main reason why the standard semiconductor band model fails in OSCs is that it does not account for the polarization

$$\mu_{\text{eff}} = \frac{n_f}{n_f + n_t} \cdot \mu_0$$

Variable Range Hopping (VRH): Miller-Abrahams VRH Rate and Network



- Dominant in disordered OSCs.
- Thermal (phonon) assisted tunneling.

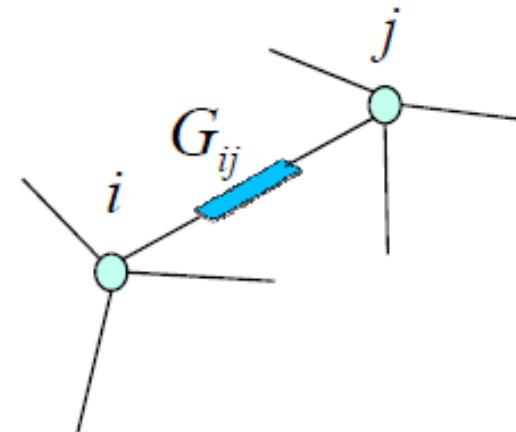
*hopping
rate*

$$\nu_{ij} = \nu_0 \exp\left(-\frac{2R_{ij}}{a}\right) \cdot \begin{cases} \exp\left(-\frac{E_j - E_i}{kT}\right) & E_j > E_i \\ 1 & E_j < E_i \end{cases}$$

*inter-site
conductance*

$$G_{ij} = G_0 \exp(-s_{ij})$$

$$s_{ij} = -\frac{2R_{ij}}{a} - \frac{|E_i - E_F| + |E_j - E_F| + |E_i - E_j|}{2kT}$$



VRH Mobility: *Effective Transport Energy*

$$E_j = E_{\text{tr}}$$

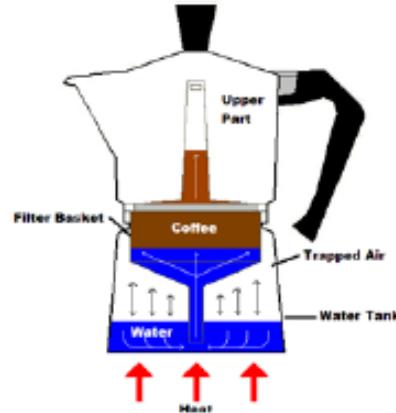
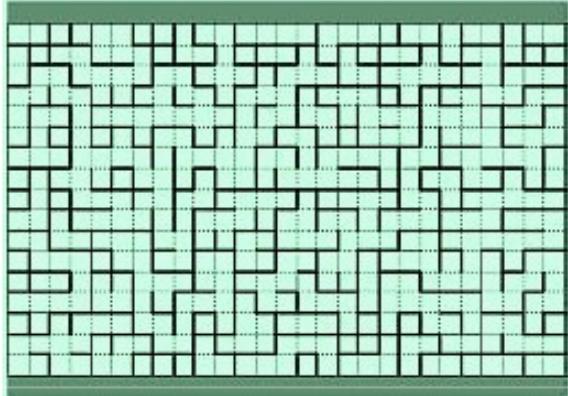
A carrier will most probably jump to a site at so-called **effective transport energy**

$$\mu_n = \frac{\mu_n}{D_n} D_n = q \underbrace{\frac{1}{n} \frac{\partial n}{\partial E_F}}_{\mu_n/D_n} \langle v_{ij} \rangle \langle R_{ij} \rangle$$

$$\langle v_{ij} \rangle = \frac{v_0}{n} \int_{-\infty}^{E_{\text{tr}}} g(E) f(E, E_F) \exp\left(\frac{E - E_{\text{tr}}}{kT}\right) dE \quad \langle R_{ij} \rangle = \left(\int_{-\infty}^{E_{\text{tr}}} g(E) dE \right)^{-1/3}$$

$$\int_{-\infty}^{E_{\text{tr}}} g(E) [1 - f(E, E_F)] (E_{\text{tr}} - E)^3 dE = \frac{6}{\pi} \left(\frac{kT}{a}\right)^3$$

VRH Mobility: Percolation Theory



$$G_{ij} = G_0 \exp(-s_{ij})$$

$$s_{ij} = -\frac{2R_{ij}}{a} - \frac{|E_i - E_F| + |E_j - E_F| + |E_i - E_j|}{2kT}$$

$$G_c = G_0 \exp(-s_c)$$

$$G_{ij} > G_c$$

$$B_c(s_c) = \frac{N_b}{N_s} = \frac{\int g(E) \theta(s_c - s_{ij}) dR_{ij} dE_i dE_j}{\int g(E) \theta(s_c kT - |E - E_F|) dE} \cong 2.8$$

$$\mu_n = \frac{\sigma_0}{qn} \exp(-s_c)$$

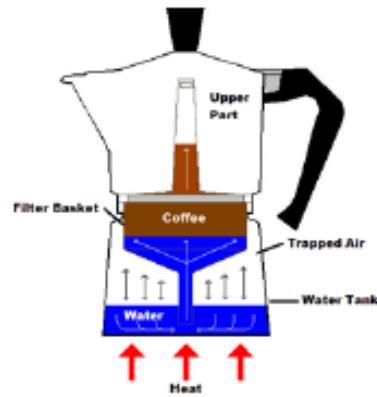
VRH Mobility: *High Electric Field*

$$\mu_n(F, n, T) = \mu_n(n, T) \exp\left(\frac{\delta\sqrt{F}}{kT}\right)$$

$$F < 2 \cdot 10^6 \frac{V}{cm}$$

- Empirical model obtained fitting Monte-Carlo numerical experiments.
- For higher electric fields the mobility saturates and decrease with electric field intensity.
- In OFET modeling it is important to separate the vertical and lateral electric field components.

Sheet Channel Conductivity



Vissenberg and Matters, Phys. Rev. B, 1998.

$$\sigma = \sigma_0 \left\{ \frac{\pi(T_0/T)^3}{(2\alpha)^3 B_c} n_{i0} \exp \left[\frac{q(\varphi - \varphi_n)}{kT_0} \right] \right\}^{T_0/T}$$

$$n(T) = n_i(T) \exp \left[\frac{q(\varphi - \varphi_n)}{kT_0} \right] \quad n_i(T) = n_{i0} \frac{\pi T / T_0}{\sin(\pi T / T_0)}$$

$$G'_c = \mu_c (-Q'_c)$$

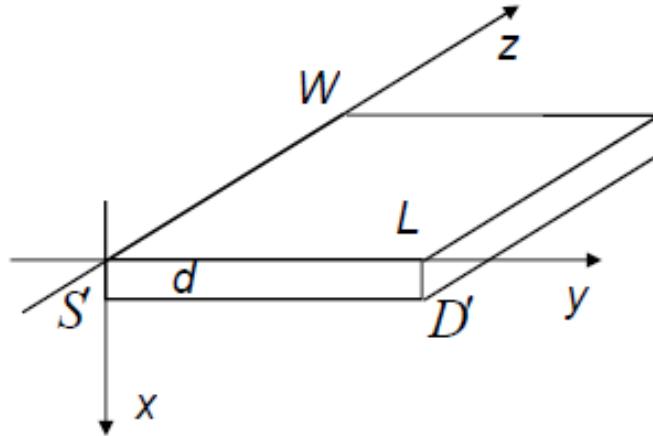
$$\mu_c = \mu_c^0 \left(\frac{(-Q'_c)}{C_i V_c} \right)^\gamma$$

$$V_c = \frac{\sqrt{2kT_0 n_{i0} \varepsilon_s}}{C_i}$$

$$\gamma = 2 \left(\frac{T_0}{T} - 1 \right)$$

$$\mu_c^0 = \frac{\sigma_0}{qn_{i0}} \left[\frac{n_{i0}(T_0/T)^4 \sin(\pi T / T_0)}{(2\alpha)^3 B_c} \right]^{T_0/T}$$

Intrinsic Drain-Source Current



Surface-Potential Based Model

$$I_{DS} = \frac{W}{L} \int_{V'_S}^{V'_D} G'_C(\varphi_s) \frac{d\phi_n}{d\varphi_s} d\varphi_s$$

$$\frac{d\phi_n}{d\varphi_s} \approx 1 - \frac{2V_{t0}C'_i}{Q'_C(\varphi_s)}$$

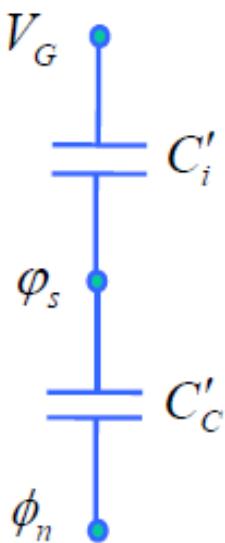
$$I_{DS} = \frac{W}{L} \int_{V'_S}^{V'_D} G'_C d\phi_n$$

Charge Based Model

$$I_{DS} = \frac{W}{L} \int_{Q'_{CS}}^{Q'_{CD}} G'_C(Q_C) \frac{d\phi_n}{dQ'_C} dQ'_C$$

$$\frac{d\phi_n}{dQ'_C} \approx \frac{1}{C'_i} - \frac{\eta V_{t0}}{Q'_C}$$

Channel Sheet Charge: Unified Charge Control Model



$$\frac{\partial \phi_s}{\partial \phi_n} \Big|_{V_G} = \frac{C'_c}{C'_c + C'_i}$$

$$\frac{\partial Q'_c}{\partial \phi_s} \Big|_{V_G} = C'_i$$

$$dQ'_c \left(\frac{1}{C'_i} + \frac{1}{C'_c} \right) = d\phi_n$$

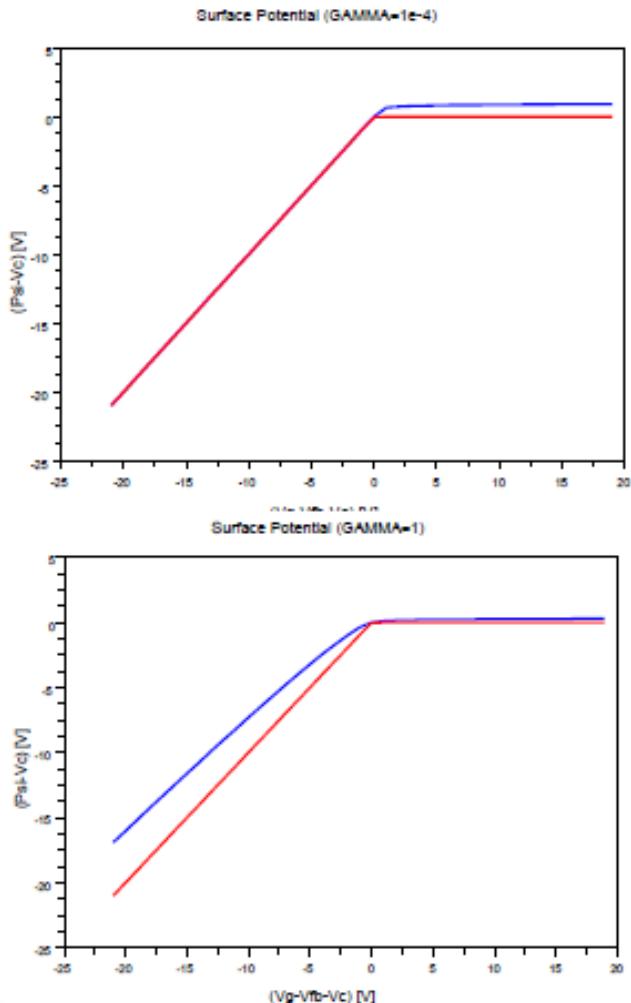
$$C'_c = -\frac{Q'_c}{\eta V_{t0}} \quad \text{critical approximation}$$

$$Q'_{CP} - Q'_c + C'_i \eta V_{t0} \ln \left(\frac{Q'_c}{Q'_{CP}} \right) = C'_i (V_G - V_T - \phi_n) \quad Q'_{CP} = -\eta C'_i V_{t0}$$

Useful approximate solution
(Fjeldly, Ytterdal, Shur:
Introduction to Device Modeling
and Circuit Simulation, 1998.)

$$Q'_c = Q'_{CP} \ln \left[1 + \frac{1}{2} \exp \left(\frac{V_G - V_T}{\eta V_{t0}} \right) \right]$$

Channel Sheet Charge: Surface Potential Equation



Exponential DOS carrier concentration

$$n = n_i(T) \exp\left[\frac{q(\phi - \phi_n)}{kT_0}\right]$$

Accumulation operation mode

$$(V_G - V_{FB} - \varphi_s)^2 = V_{t0} \gamma^2 \cdot h\left(\frac{\varphi_s - \phi_n}{V_{t0}}\right)$$

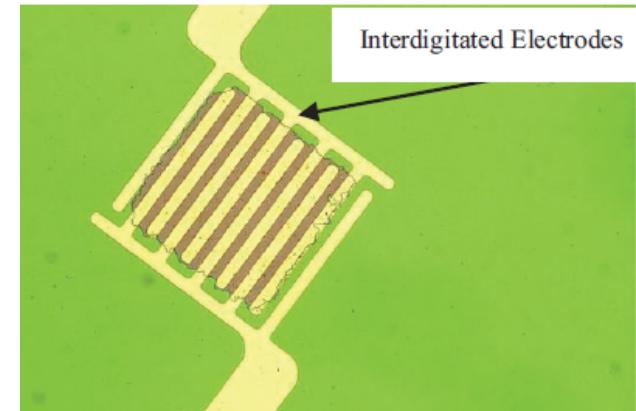
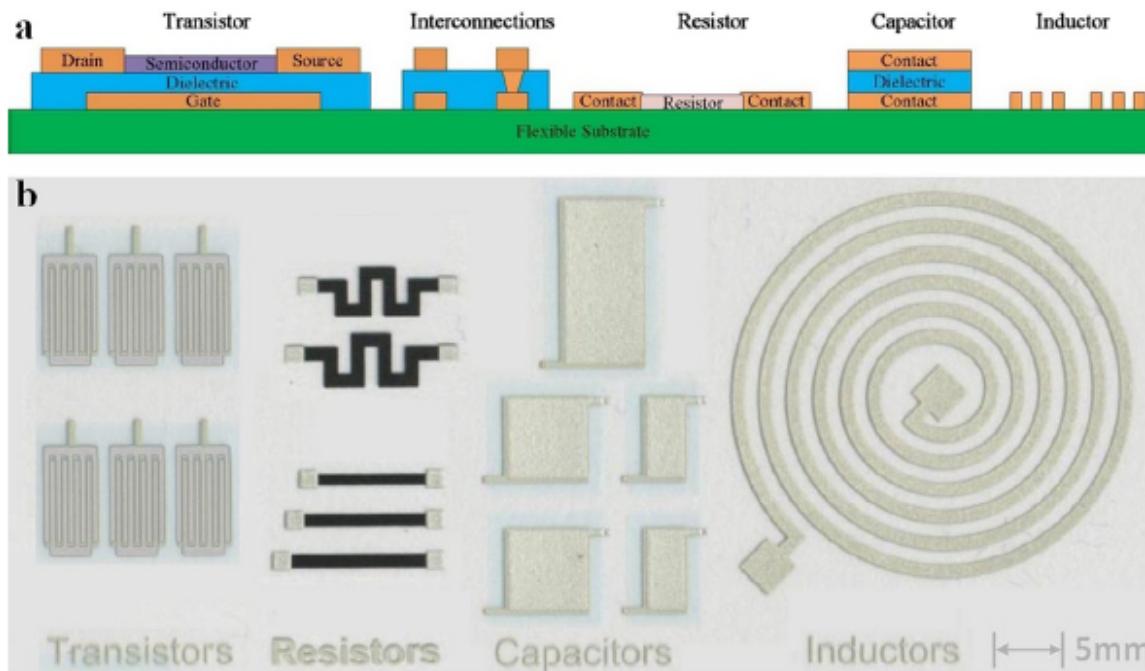
$$\gamma = \frac{\sqrt{2q\varepsilon_s n_i(T)}}{C'_i}$$

$$h(x) = \exp(x) - x - 1$$

$$Q'_c = -C'_i(V_G - V_{FB} - \varphi_s)$$

There is an approximate analytical solution
(Gildenblat, et al., IEEE J. SSC, 2004)

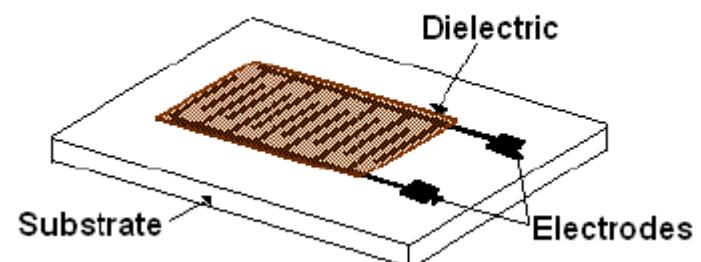
Beberapa Contoh Desain (yg lain)



Optical microscope images of micro interdigitated electrodes

(a) Cross section of printed transistor, interconnections, resistor, capacitor and inductor, and (b) their microphotographs.

Organic Electronics 15 (2014) 701–710



Structure of a thick film interdigitated capacitor

Tugas III

Buat Topik Research
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Tema: Developing Green Energy

Acknowledgment

SILVACO

We want to thank Prof. Iniguez and his group for valuable recommendations regarding compact organic TFT modelling.

This work is supported by the UK Technology Strategy Board through the PMOS project TP/J2519J.